REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED *(From – To)*
8 Jul 2015	Conference Proceedings	Oct 2006 – Sep 2007

4. TITLE AND SUBTITLE

Visibility of Monocular Symbology in Transparent Head-Mounted Display Applications

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

Marc Winterbottom, Robert Patterson, B Pierce, James Gaska, Steven Hadley

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

USAF School of Aerospace Medicine
USAFSAM/FHO
2510 Fifth St.
Wright-Patterson AFB, OH 45433-7913

8. PERFORMING ORGANIZATION REPORT NUMBER

AFRL-SA-WP-JA-2015-0034

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSORING/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT

Distribution A: Approved for public release; distribution is unlimited. Case Number: 88ABW-2015-1675, 27 Mar 2015

13. SUPPLEMENTARY NOTES

Published in Proc. of SPIE Vol. 9470 94700Z

14. ABSTRACT

With increased reliance on head-mounted displays (HMDs), such as the Joint Helmet Mounted Cueing System and F-35 Helmet Mounted Display System, research concerning visual performance has also increased in importance. Although monocular HMDs have been used successfully for many years, a number of authors have reported significant problems with their use. Certain problems have been attributed to binocular rivalry when differing imagery is presented to the two eyes.
With binocular rivalry, the visibility of the images in the two eyes fluctuates, with one eye's view becoming dominant, and thus visible, while the other eye's view is suppressed, which alternates over time. Rivalry is almost certainly created when viewing an occluding monocular HMD. For semi-transparent monocular HMDs, however, much of the scene is binocularly fused, with additional imagery superimposed in one eye. Binocular fusion is thought to prevent rivalry.
The present study was designed to investigate differences in visibility between monocularly and binocularly presented symbology at varying levels of contrast and while viewing simulated flight over terrain at various speeds. Visibility was estimated by measuring the presentation time required to identify a test probe (tumbling E) embedded within other static symbology. Results indicated that there were large individual differences, but that performance decreased with decreased test probe contrast under monocular viewing relative to binocular viewing conditions. Rivalry suppression may reduce visibility of semi-transparent monocular HMD imagery. However, factors, such as contrast sensitivity, masking, and conditions such as monofixation, will be important to examine in future research concerning visibility of HMD imagery.

15. SUBJECT TERMS

Head-mounted displays, HMD, binocular rivalry

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			Marc Winterbottom
U	U	U	SAR	13	19b. TELEPHONE NUMBER *(include area code)*

Visibility of Monocular Symbology in Transparent Head-Mounted Display Applications

M. Winterbottom[*1], R. Patterson[2], B. Pierce[3], J. Gaska[1], and S. Hadley[1]

[1]711[th] Human Performance Wing, USAF School of Aerospace Medicine, Operational Based Vision Assessment Laboratory, Wright-Patterson AFB, USA, 45433; [2]711[th] Human Performance Wing, Human Effectiveness Directorate, Wright-Patterson AFB, USA, 45433; [3]Certified Human Factors Professional, Tempe, AZ, USA, 85282

ABSTRACT

With increased reliance on head-mounted displays (HMDs), such as the Joint Helmet Mounted Cueing System and F-35 Helmet Mounted Display System, research concerning visual performance has also increased in importance. Although monocular HMDs have been used successfully for many years, a number of authors have reported significant problems with their use. Certain problems have been attributed to binocular rivalry when differing imagery is presented to the two eyes.

With binocular rivalry, the visibility of the images in the two eyes fluctuates, with one eye's view becoming dominant, and thus visible, while the other eye's view is suppressed, which alternates over time. Rivalry is almost certainly created when viewing an occluding monocular HMD. For semi-transparent monocular HMDs, however, much of the scene is binocularly fused, with additional imagery superimposed in one eye. Binocular fusion is thought to prevent rivalry.

The present study was designed to investigate differences in visibility between monocularly and binocularly presented symbology at varying levels of contrast and while viewing simulated flight over terrain at various speeds. Visibility was estimated by measuring the presentation time required to identify a test probe (tumbling E) embedded within other static symbology. Results indicated that there were large individual differences, but that performance decreased with decreased test probe contrast under monocular viewing relative to binocular viewing conditions. Rivalry suppression may reduce visibility of semi-transparent monocular HMD imagery. However, factors, such as contrast sensitivity, masking, and conditions such as monofixation, will be important to examine in future research concerning visibility of HMD imagery.

Keywords: Head-mounted displays, HMD, binocular rivalry

1. INTRODUCTION

Historically, a number of technological advances have been derived from the ability of humans to augment the use of their visual system using optical technology (e.g., telescopes, microscopes, periscopes). During the past several decades, another technological advance has been the development of head- or helmet-mounted displays (HMDs), which allows synthetic information to be projected conveniently in front of an observer. An HMD presents pictorial or symbolic information to either one eye or both eyes of a user by way of one or two miniature visual displays mounted on the head via a helmet or other kind of arrangement.[1–4] When information is presented to one eye, it is called a monocular HMD; when the same information is presented to two eyes, it is called a biocular HMD; and when information with binocular parallax (also called binocular disparity, the cue for stereoscopic depth perception) is presented to two eyes, it is called a binocular HMD.

Monocular HMDs have been used in a variety of applications, including aviation,[5] displays for dismounted infantry,[6] and personal entertainment.[7] Often, significant issues with their use have been reported and attributed to a phenomenon

[*] marc.winterbottom@us.af.mil

Display Technologies and Applications for Defense, Security, and Avionics IX; and Head- and Helmet-Mounted Displays XX, edited by Daniel D. Desjardins, Peter L. Marasco, Kalluri R. Sarma, Paul R. Havig, Michael P. Browne, James E. Melzer, Proc. of SPIE Vol. 9470, 94700Z · © 2015 SPIE · CCC code: 0277-786X/15/$18 · doi: 10.1117/12.2179091

called binocular rivalry.[5,7,8] Binocular rivalry occurs when the two eyes receive very different stimulation, resulting in a state of competition between the eyes, where one eye inhibits the visual processing of the other eye. The visibility of the images in the two eyes fluctuates, with one eye's view becoming visible while the other eye's view is suppressed, which reverses over time. Importantly, during binocular rivalry, portions of stimulation in only one eye gain access to higher visual processing stages at any one time.[9] The perceptual confusion known as rivalry arises because the two eyes signal to the brain that two different objects exist at the same time and location.[10] Binocular rivalry is important to study because it represents a visual process by which information or signals may be missed while using an HMD. However, much of the evidence for the existence of rivalry when HMDs are used under real-world conditions is anecdotal in nature or based on subjective measures. For example, questionnaires and general feedback from pilots and other users are probably most often used to evaluate potential effects of rivalry with the use of HMDs in aviation.[5,8,12] Another frequently used technique is rating or tracking target stimuli visibility.[12] The difficulty involved with investigating a phenomenon such as rivalry, which may be intermittent and piecemeal, especially under applied conditions, may in some cases necessitate the use of primarily subjective methods. However, it is not clear that observers are always aware of decrements in performance attributable to rivalry. Previous research has also shown that reaction time in a simulated targeting task was slower for monocular symbology compared to binocular symbology and that observers clearly preferred binocular imagery over monocular imagery.[13] However, it is also possible that training with a monocular HMD might improve targeting task performance.[14] Although it is not clear whether training has any effect on the occurrence of rivalry. Some research suggests that rivalry is influenced by conscious attention, while other research suggest that it is primarily driven by low level stimulus factors[15]

We have previously described how a variety of human factors issues has affected (and sometimes discouraged) the use of HMDs,[2] and more specifically, we have described the factors that may affect the occurrence of binocular rivalry in HMDs.[16] These factors have been studied extensively under classic rivalry conditions (where completely different images are presented to the two eyes, for example, a vertical grating in one eye and a horizontal grating in the other eye) and include orientation difference,[17] contour density,[18] spatial frequency,[19] color,[20] and motion.[21,22] Here, we focus on two factors (motion and target contrast) that may affect binocular rivalry in a specific situation – the viewing of monocularly presented information against a background viewed binocularly. This is similar to the viewing condition with the use of a monocular transparent HMD and uses much more complex imagery than is typically used in binocular rivalry research. However, we used methods more similar to those reported in the basic research literature, the use of a probe stimulus to measure rivalry suppression,[23] rather than relying solely on subjective reports of the occurrence of rivalry.

The Air Force has used a monocular HMD called the Joint Helmet Mounted Cueing System (JHMCS) very successfully for a number of years, and this system conveys some critical advantages to a pilot engaged in combat. Additionally, the Army has used another monocular HMD, the Integrated Helmet and Display Sighting System, very successfully in the Apache helicopter for decades. However, there have been some anecdotal reports of issues with visibility of the monocularly presented imagery with each of these displays under certain conditions. We investigated this issue as preparation for integration of a simulated version of the JHMCS into existing flight simulators at the Air Force Research Laboratory. The U.S. Air Force School of Aerospace Medicine (USAFSAM), Operational Based Vision Assessment Laboratory is also investigating individual differences in quality of vision that may affect performance and comfort when using HMDs.

Previous research suggests that rivalry does not occur under conditions we will refer to as partial fusion, where two eyes view a common scene, but additional information is presented to one of the eyes,[24,25] as would be the case for a transparent monocular HMD like the JHMCS. However, some research shows that rivalry may occur separately in different visual pathways, and the chromatic pathways have been shown to be more susceptible to rivalry than the achromatic pathways,[9,26] Moreover, other research has shown that binocular rivalry and binocular fusion may occur simultaneously within different spatial frequency bands.[27] Thus, it is possible that binocular fusion of the background might not mitigate against the binocular rivalry that could occur when a monocular semi-transparent HMD is worn because either the rivalry would occur in the chromatic pathways while fusion occurred in the achromatic pathway, or vice versa, or the rivalry would occur in a different frequency band than the fusion. We have shown previously that visibility was reduced for a monocularly viewed alphanumeric character under partial fusion conditions similar to those we will describe here, but only with static imagery and at a fixed contrast.[28] In the present study, we examine the effect of motion (flight over terrain) and target contrast on the visibility of monocularly viewed symbology.

2. EXPERIMENT 1: EFFECT OF MOTION

Methods

Observers

Six observers with normal or corrected to normal vision volunteered for this experiment. All subjects were provided informed consent and all methods received Institutional Review Board approval. One of the authors served as a research participant. Observers were screened for normal visual function (near/far acuity, stereo vision, phoria) using an Optec Vision Tester (Stereo-Optical Corp.).

Apparatus and Stimuli

Two visual displays were used: a VDC Sim 1600 LCoS projector and an Eizo Flexscan 985 Ex LCD flat panel display. The LCoS display rear-projected an image onto a small DA-Lite DASS screen, which was viewed through a beam splitter to allow the symbology and out-the-window (OTW) display (see Figure 1) to be optically combined. The symbology was similar to that used with the JHMCS (see Figure 2). The combination of the LCoS display and beam splitter was referred to as the (simulated) HMD display (HMD). The LCD flat panel displayed a desert terrain scene in the desert southwest and was referred to as the OTW, or background, display. The viewing distance to each display was 36 in.

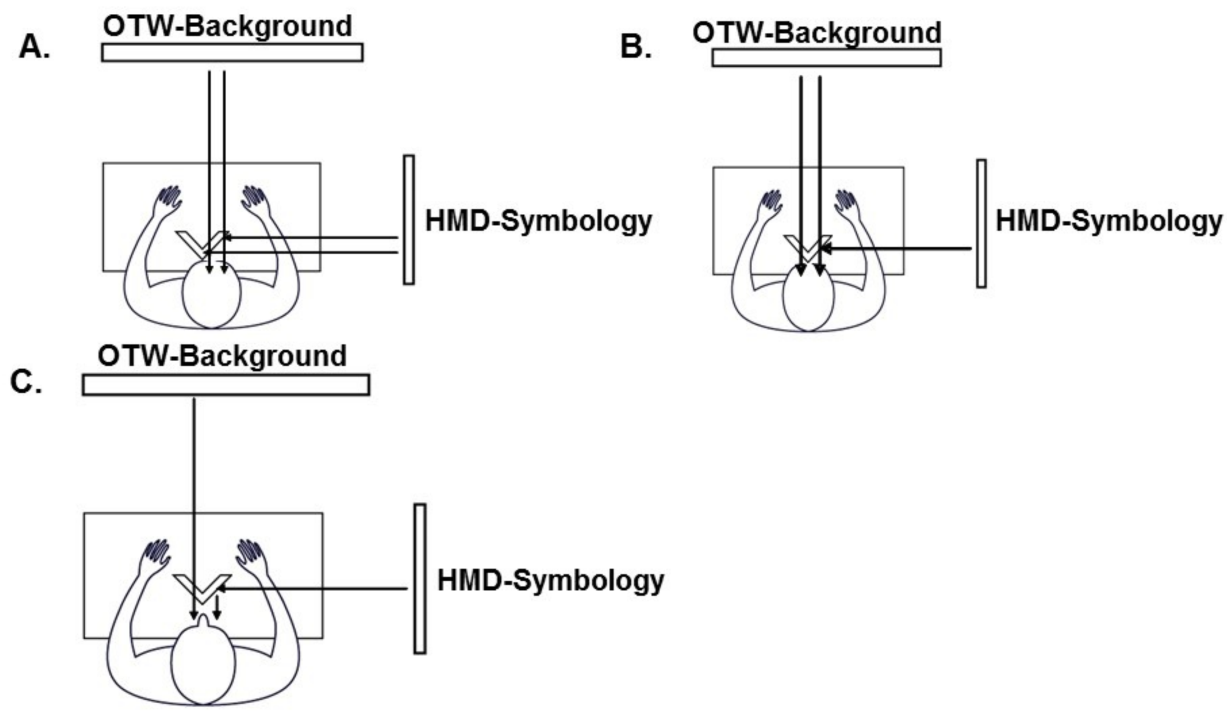


Figure 1. Diagrams depicting three of the viewing conditions used for Experiments 1 & 2. A. Full-Fusion (binocular) condition – two eyes view both the OTW scene and the HMD scene. B. Partial-Fusion (mixed binocular and monocular) condition – two eyes view the OTW scene and one eye also views the HMD scene. C. No-Fusion (dichoptic) condition – one eye views the OTW scene and the other views the HMD scene.

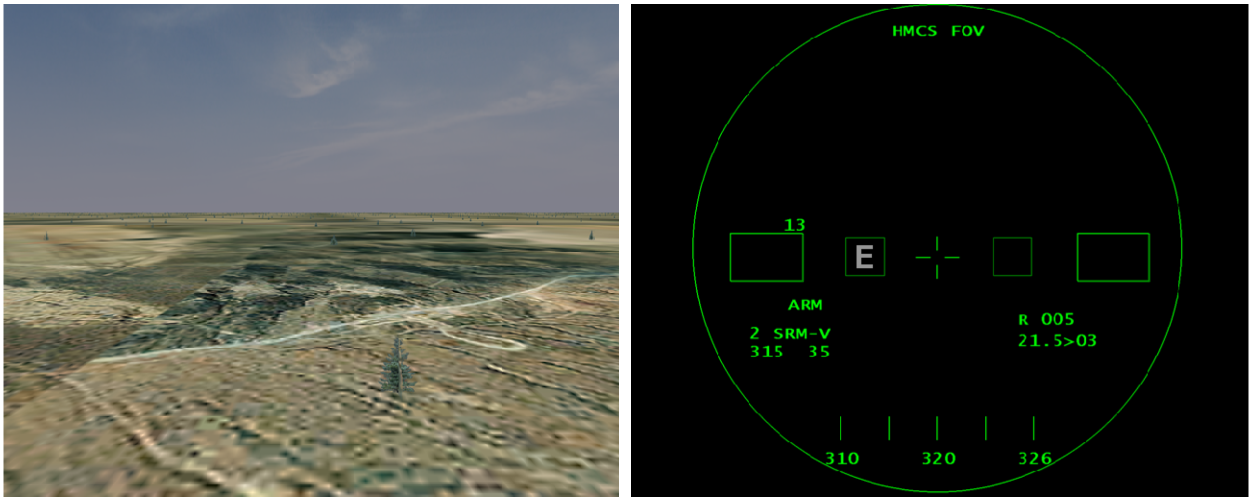


Figure 2. Desert terrain displayed on OTW view (left) and symbology and target letter displayed on HMD view.

To equalize the luminance presented to the two eyes, the OTW display was also viewed through a beam splitter. Additionally, neutral density filters were fitted to the LCoS display to match the luminance of the LCD flat panel display. The target stimulus, or test probe, was a white block letter E, with a contrast of approximately 0.2 [Weber contrast: $(L_1-L_2)/L_2$], which was presented for a brief duration (16.7 to 2137.6 ms). Target letter size was 0.7 degrees. Target contrast was calibrated using an IQCam model 500c imaging photometer. A calibration procedure using a photodiode was also employed to ensure that the target presentation duration was accurate. For the moving terrain conditions, the target appeared over background imagery of varying luminance. Thus, target contrast varied from trial to trial. However, average contrast was maintained at 0.2. The target could appear on either side of a fixation cross (approximately 1 deg. to the left or right). Thus, on any given trial, the target could appear at one of four locations left or right, HMD or OTW display. Observers reported that the OTW and HMD targets were nearly identical and could not recognize on which display the target had appeared. Three speeds of motion, or flight over terrain, were selected: 0.0 (low), 0.3 (medium), and 3.0 (high) eye-heights/second (0, 36, 324 kph). These ego-motion speeds correspond to no motion, low speed (similar to that encountered when walking or flying at high altitude), and high speed (similar to that encountered while riding a bike or flying at low altitude), respectively. The simulated altitude was approximately 30 m. The terrain was generally flat, but because southwestern desert terrain near Nevada was used for the simulation (using digital terrain elevation data and photo realistic imagery), there was some variation in height above terrain during the flight. A PC-based image generator (MetaVR) was used to create and generate the desert terrain imagery shown on the OTW display.

Procedure

Observers were seated with their heads stabilized using a chin rest. Three viewing conditions were presented: binocular control (full fusion), monocular HMD (partial fusion), and dichoptic (no-fusion). Thus, three levels of state of fusion (full, partial, and none) were tested in different blocks of trials. Additionally, the three speeds of flight over terrain (0.0, 0.3, and 3.0 eye-heights/second) were tested in different blocks of trials. Target letter duration was varied from 0.017 to 2.14 seconds (1 to 128 video frames) in different blocks of trials. In each block of trials there were 80 target presentations, and accuracy and reaction time in identifying the orientation of the target letter E were recorded. Thus, each participant viewed at least 20 trials x 4 locations x 7 durations x 3 speeds = 1,680 target presentations. A psychometric function, based on percentage correct for each target duration, was generated for each viewing condition and display (percentage correct was averaged over left/right locations).

Results

Figure 3 shows two psychometric functions for one participant in the no-motion binocular, full fusion, control condition (left) and two for the partial fusion condition (right). As shown, performance on the HMD-displayed targets is reduced for this participant (i.e. when the test probe is superimposed monocularly). Thresholds were estimated for each participant, viewing condition, and display location (OTW-displayed or HMD-displayed) according to a best-fitting psychometric function:

$$\Psi = \gamma + \left(1 - e^{-\left(\frac{t}{\alpha}\right)^{\beta}}\right) * (1 - \gamma - \lambda)$$

Where t is the log of the target presentation duration in milliseconds, α is the threshold duration value, β is the slope of the function, λ is the number of finger errors/mistakes, and γ is the chance/guessing level (0.25 for a 4 AFC task).

Figure 4 shows average thresholds (across subjects) for each target display, viewing condition, and speed. For OTW-displayed targets, thresholds are approximately equal for the binocular and monocular conditions, but generally higher for the dichoptic viewing condition. However, HMD-displayed monocular targets generally resulted in higher thresholds compared to either the binocular or dichoptic viewing conditions.

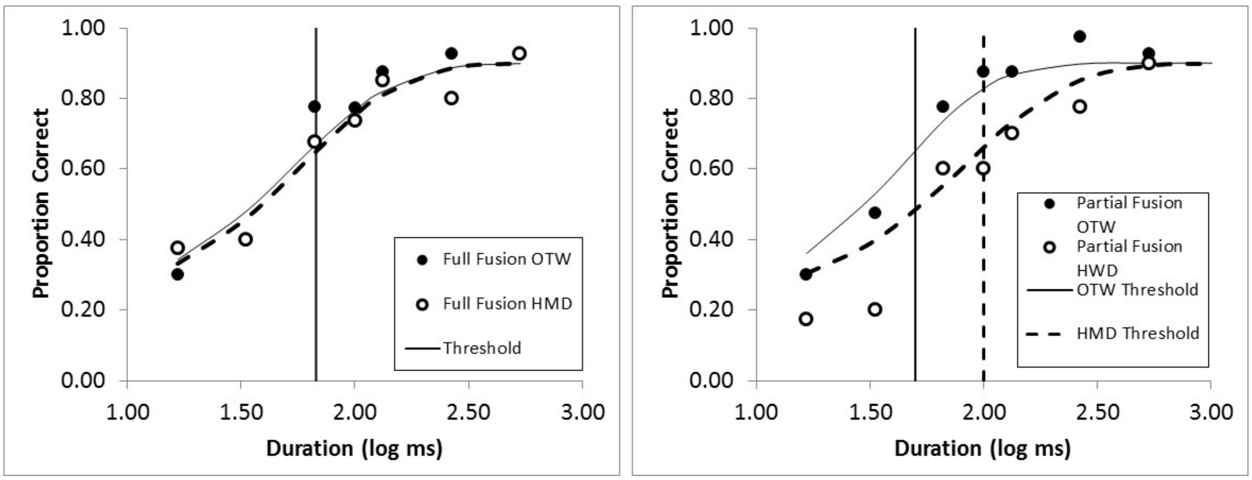


Figure 3. Proportion correct target recognition for one subject for OTW-displayed targets (solid circles) and HMD-displayed targets (open circles) and the binocular (left) and monocular (right) conditions (at 0.0 eye-height/s speed). Full fusion OTW, Full Fusion HMD, and Partial Fusion OTW targets are all presented binocularly, and result in similar thresholds while partial fusion HMD targets are presented monocularly. Estimated thresholds are indicated by the vertical lines.

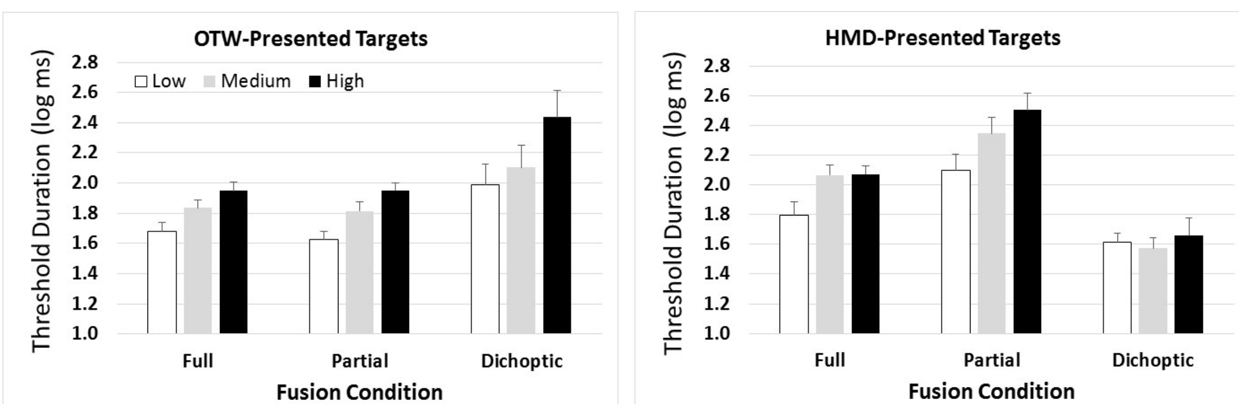


Figure 4. Thresholds in log milliseconds (ms) for each display and viewing condition in Experiment 1. Thresholds for OTW-displayed targets are shown on the left. Thresholds for HMD-displayed targets are shown on the right.

Figure 5 shows the average proportion change in thresholds relative to the binocular full fusion condition for the partial fusion viewing condition (left) and dichoptic viewing condition (right) for each speed and target location (OTW vs. HMD). Thresholds tended to be higher for the dichoptic viewing condition for OTW-displayed monocular targets relative to the binocular full fusion condition, but little changed, or even a small improvement in performance, relative to the control for dichoptic HMD-presented targets. For the partial fusion condition, the reverse is true. Threshold differences are higher for the HMD-displayed targets. A repeated-measures analysis of variance (ANOVA) showed that the effects of fusion, interaction of speed and display, and interaction of fusion and display were all significant ($p < 0.05$). No other effects were significant. In particular, the overall effect of speed was not significant. A paired sample t-test shows that, for the specific comparison of interest, thresholds for the partial fusion HMD-displayed targets are higher than those for the binocular control condition [$t(17) = 7.2$, $p < 0.001$]. Additionally, thresholds in the partial fusion HMD condition did not differ significantly in comparison to the dichoptic OTW condition [$t(16) = 0.34$, $p = 0.74$]. Thresholds for the dichoptic HMD-displayed targets were significantly lower than those for the partial fusion OTW-displayed targets [$t(17) = -5.5$, $p < 0.001$].

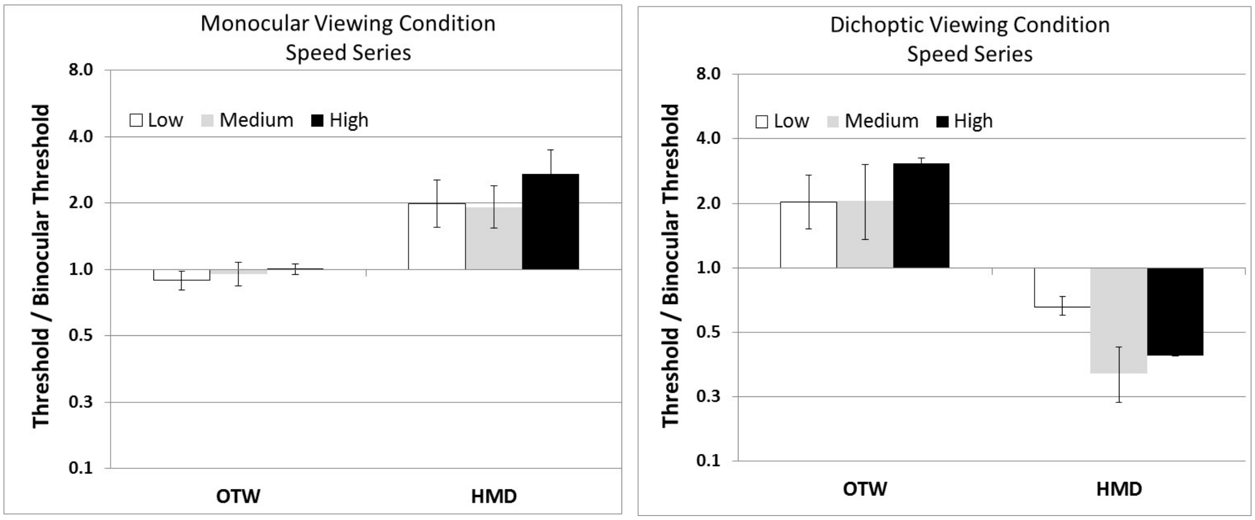


Figure 5. Difference in thresholds relative to the full fusion control condition for each display, viewing condition, and speed.

Discussion

The results of Experiment 1 show that the visibility of monocularly presented symbology, similar to that of the JHMCS, is reduced relative to nearly identical binocular symbology of equal (relatively low) contrast. However, moving terrain did not appear to reduce the visibility of partial fusion HMD-presented targets relative to the binocular control condition. Thus, moving imagery did not appear to lead to greater suppression of the simulated transparent HMD symbology as predicted. In contrast, the significant interaction between fusion condition and speed suggests that moving imagery may have actually reduced (improved) thresholds for the dichoptic HMD-presented targets. This is the opposite of what was predicted based on a review of the literature on binocular rivalry.

A significant amount of research does indicate that monocular thresholds tend to be higher than binocular thresholds by a factor of approximately 1.4 due to binocular summation. Although estimates of the increases in thresholds attributed to a lack of binocular summation are highly variable[29]. Here, the proportional increase in thresholds for the partial fusion HMD-presented targets is greater than 1.4, suggesting that rivalry suppression could be occurring under partially fused monocular viewing conditions (i.e. thresholds worsen more than might be predicted by lack of summation alone). However, ego-motion does not appear to increase this suppression.

Notably, under the dichoptic viewing condition in the present experiment, the results appear to be the opposite of that predicted by earlier research – thresholds were higher for targets presented on the same display as the moving imagery and lower for targets presented on the display with no moving imagery. Subjectively, it appeared that rivalry suppression was occurring in the dichoptic viewing condition. However, it may be that the suppression actually aided target recognition for the HMD-presented targets. During rivalry alternation, when the background terrain imagery may have been partially suppressed, the HMD targets appeared against a gray background and were very apparent (although maintained at 0.2 contrast, and with the same average luminance as the background scene). Thus selective attention may have played a role in target recognition. These somewhat unexpected results may also suggest that additional factors may also affect the visibility of the targets. For example, effects of masking due to the textured background may have been reduced/removed for HMD-presented targets, but not for dichoptic OTW-presented targets (see discussion below). Finally, although we tested observers for eye dominance (1 was right-eye dominant, 4 were left eye dominant, and 1 was neutral), the data showed no significant eye-dominance effect for this experiment. A much larger number of observers would be required to evaluate individual differences in vision such as eye dominance.

3. EXPERIMENT 2: EFFECT OF CONTRAST

Experiment 2 was designed to investigate the effect of target contrast on suppression under partial-fusion conditions.

Methods

Observers

Six observers with normal or corrected to normal vision volunteered for this experiment. All subjects were provided informed consent and all methods received Institutional Review Board approval. All observers were screened for normal visual function (near/far acuity, stereo vision, phoria) using an Optec Vision Tester (Stereo-Optical Corp.).

Apparatus and Stimuli

The apparatus was identical to that used in Experiment 1. The stimuli used for Experiment 2 were very similar to Experiment 1 with the exception that target contrast (the contrast of the letter E against the background) was varied instead of speed. The contrast levels selected were 0.2 (low), 0.4 (medium), and 1.4 (high). Flight over terrain was held constant at 0.03 eye-height/second (36 kph). This is equal to the medium speed in experiment 1. Because of the moving terrain background, target contrast again varied from trial to trial. However, average contrast was maintained for each contrast condition (0.2, 0.4, or 1.4).

Procedure

The procedure was similar to that of Experiment 1 except that target contrast was varied across blocks of trials rather than speed.

Results

Figure 6 shows average log thresholds for each display, viewing condition, and contrast level. As shown, thresholds are approximately equal for the full fusion and partial fusion conditions for OTW-displayed targets, but generally higher for the dichoptic viewing condition. However, for HMD-displayed targets, monocular, partial fusion targets resulted in higher thresholds compared to either the binocular or dichoptic viewing conditions. For the highest contrast, many of the observers could accurately identify target orientation for presentation durations of just 1 frame (16.7 ms).

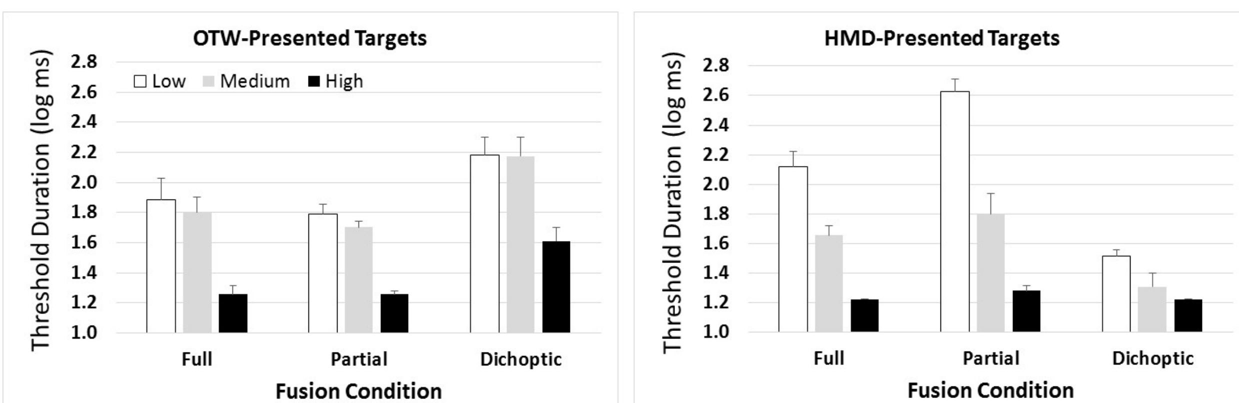
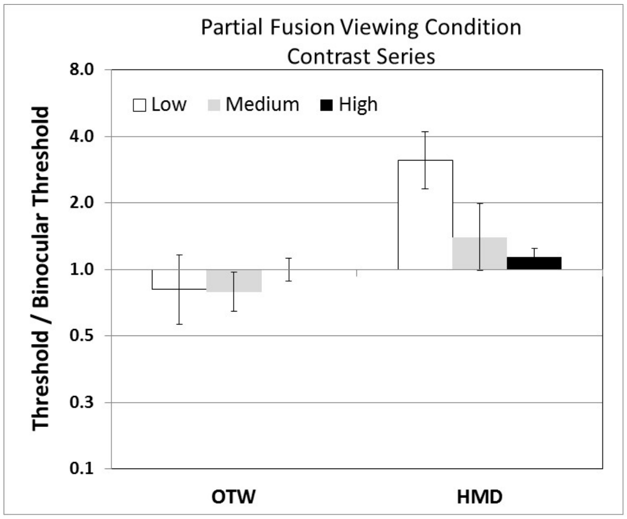


Figure 6. Average thresholds for OTW-displayed targets (left) and simulated HMD-displayed targets (right) for each viewing condition and contrast level.

Figure 7 shows the proportion change in target duration thresholds relative to the binocular full fusion condition for partial fusion targets (left) and dichoptic targets (right) for each display condition and contrast. As shown, thresholds for the partial fusion condition are similar to those for the binocular condition. Thresholds for partial fusion HMD-presented targets are elevated for the lowest contrast. Thresholds for dichoptic OTW-presented targets are elevated relative to the binocular full fusion condition. Similar to Experiment 1, thresholds for dichoptic HMD-presented targets are decreased relative to binocular full fusion targets.

A repeated measures ANOVA showed that the interaction of contrast x fusion condition, fusion condition x display, and contrast x fusion x display were significant ($p < 0.05$). No other effects were significant. Further analyses revealed that thresholds for partial fusion HMD-presented targets were significantly higher than thresholds for partial fusion OTW-presented targets ($t = -2.74$, $p = 0.015$). Thresholds for dichoptic OTW-presented targets were significantly higher than partial fusion OTW-presented targets ($t = -2.28$, $p = 0.04$). Thresholds for dichoptic OTW-presented targets were not significantly different than thresholds for partial fusion HMD-presented targets ($t = -1.34$, $p = 0.2$). Thresholds for dichoptic HMD-presented targets were again lower than thresholds for partial fusion OTW-presented targets. Relative to the control condition, thresholds for the 0.2 (low) contrast condition were significantly higher than thresholds for the 1.4 (high) contrast condition [$t(4) = 3.91$, $p = 0.017$].



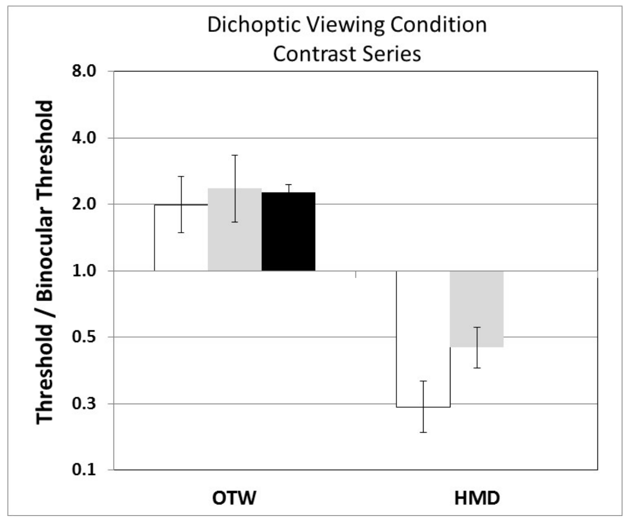


Figure 7. Proportion change in target duration thresholds in milliseconds relative to the binocular full fusion condition for the partial fusion condition (left) and dichoptic condition (right) for each display and contrast level.

Discussion

Experiment 2 showed that reduced target contrast had a greater effect on the visibility of partial fusion HMD-presented targets in comparison to binocularly viewed targets. For low contrast targets the visibility of partially fused, monocular imagery was less than that of dichoptically viewed imagery. However, this decrement in performance was largely eliminated when the contrast of the targets was raised to 1.4. This could serve as a useful guideline for monocularly presented imagery and may have implications for maximum luminance/contrast standards for these devices.

While rivalry suppression is one possible explanation for reduced visibility with the use of monocular imagery similar to that for monocular transparent HMDs, another possibility is that the textured background decreased discriminability of the target due to visual masking. Masking is the impairment of a signal by another pattern[30]. For example, research shows that search times for words against textured backgrounds is affected by both contrast and texture type (e.g. spatial frequency similar to that of the target). Similar to the current results, search times for low contrast text increased for certain textures, but this effect diminished for high contrast text[31]. As noted above, it is well known that binocular summation reduces threshold contrast by approximately 40% for binocularly viewed targets relative to monocular targets.[29,32] Thus, monocular targets, through lack of binocular summation, may lower effective contrast below this critical threshold, resulting in decreased performance (increased threshold durations) during monocular viewing.

Another possibility is that individual differences in contrast sensitivity, or undiagnosed visual conditions such as monofixation or suppression, may have reduced the visibility of the monocularly presented targets for some observers. Based on data collected by USAFSAM, although vision screening devices such as the Optec are useful for identifying gross deficiencies, a considerable amount of individual variability in quality of vision may go undetected. Unequal contrast sensitivity across the two eyes combined with lack of binocular summation may have reduced contrast to near threshold in the current research for some observers while remaining above a critical contrast threshold for other observers. Although all observers were screened for normal vision using a standard Optec vision tester, ongoing research at USAFSAM has demonstrated that standard pass/fail screening tests may not be adequate. For example, an individual may pass the Optec stereo acuity test with 25 arcsec or better but may nonetheless demonstrate poor stereo acuity when tested with a more accurate threshold level test[33,34]. Figure 8 shows that duration thresholds varied by a factor of about 4 to 1 across observers in Experiment 2. More thorough vision testing will be required in future research to determine different factors that may affect performance and comfort with the use of HMDs.

Finally, although we tested observers for eye dominance again in Experiment 2 (2 were right-eye dominant, 3 were left eye dominant, and 1 was neutral), the data showed no significant eye-dominance effect for this experiment. As noted above, a much larger number of observers would be required to evaluate individual differences in vision such as eye dominance.

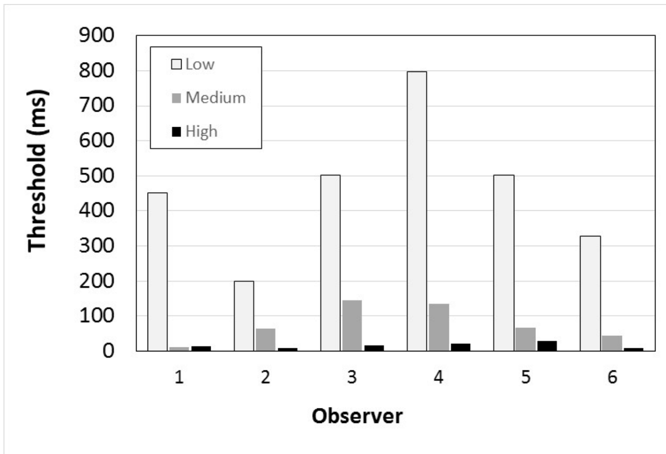


Figure 8. Thresholds for each observer and contrast level for the monocular HMD condition in Experiment 2.

4. GENERAL DISCUSSION

This research compared performance among full fusion, partial fusion, and dichoptic viewing conditions for a group of normally sighted individuals and provides preliminary data concerning visual performance with the use of HMDs such as the JHMCS and F-35 Helmet Mounted Display System (HMDS). This research provides some evidence that the visibility of monocular symbology may be reduced with the use of HMDs such as the JHMCS or F-35 HMDS – particularly with low contrast targets. Binocular rivalry is a possible explanation for the degraded performance since the proportion decrease in performance for the monocularly-presented targets exceeds 1.4, which might be expected due to lack of binocular summation. However, visual masking resulting from the operationally-relevant textured background and individual differences in quality of vision may be other important factors to consider. Because USAFSAM's Operational Based Vision Assessment (OBVA) Laboratory is tasked with generating data that can be used in the selection and retention of aircrew, future research will examine how individual differences in binocular vision capabilities are related to performance with these devices. It is clear that an individual's binocular vision capabilities can be influenced by a variety of factors such as ocular motility, fixation accuracy, acuity, and contrast sensitivity (when tested in each eye and the balance between them). A particularly relevant example is monofixation syndrome,[35] in which an individual can exhibit strong suppression to monocularly presented stimuli. It is possible that individuals with monofixation syndrome would perform very poorly under certain HMD conditions, and it may be important to identify these individuals prior to selection for pilot training. While small fixation inaccuracy (microtropia) is most often associated with this condition, reduced stereopsis can also identify these individuals.[36,37] In addition, individuals with unequal refractive power in each eye (anisometropia) have a higher incidence of reduced binocular function.[38] To address these issues, we have developed a battery of computer/monitor-based tests that can measure these visual capabilities with higher reliability than current tests used in most clinical studies. These data along with operational tasks that accurately replicate the visual conditions in the HMD devices will improve our ability to make certain that the visual capabilities of our aircrew meet or exceed those required for mission success.

ACKNOWLEDGMENTS

The views expressed are those of the authors and do not necessarily reflect the official policy or position of the Air Force, the Department of Defense, or the U.S. Government. This work was supported by U.S. Air Force Contract FA8650-05-D-6502 to Link Simulation and Training (a division of L3 Communications Corp.). Distribution A: approved for public release (88ABW-2015-1675, 31 Mar 2015).

REFERENCES

1. Melzer, J. & Moffitt, K. *Head-mounted displays: designing for the user*. (McGraw-Hill, 1997).

2. Patterson, R., Winterbottom, M. D. & Pierce, B. J. Perceptual Issues in the Use of Head-Mounted Visual Displays. *Hum. Factors* **48,** 555–573 (2007).

3. Velger, M. *Helmet-mounted displays and sights*. (Artech House Publishers, 1998).

4. Bayer, M., Rash, E. & Brindle, J. in *Helmet-Mounted Displays: Sensation, Perception, and Cognition Issues* (eds. Rash, C., Russo, M., Letowski, T. & Schmeisser, E.) 47–103 (U.S. Army Aeromedical Research Laboratory, 2009).

5. Behar, I. *et al. Visual Survey of Apache Aviators (VISAA) USAARL Report No . 90-15*. (1990).

6. Glumm, M. *et al. A Comparison of Soldier Performance Using Current Land Navigation Equipment with Information Integrated on a Helmet-Mounted Display. ARL-TR-1604*. (1998). at <http://oai.dtic.mil/oai/oai?verb=getRecord&metadataPrefix=html&identifier=ADA345254>

7. Häkkinen, J. A Virtual Display for Mobile Use. *SID Symp. Dig. Tech. Pap.* **35,** 1586–1589 (2004).

8. Temme, L. *et al.* in *Helmet-Mounted Displays: Sensation, Perception, and Cognition Issues* (eds. Rash, C., Russo, M., Letowski, T. & Schmeisser, E.) 497–504 (U.S. Army Aeromedical Research Laboratory, 2009).

9. Howard, I. *Seeing in depth: Vol. 1. Basic mechanisms*. (Porteous, 2002).

10. Blake, R. A Primer on Binocular Rivalry, Including Current Controversies. *Brain Mind* **2,** 5–38 (2001).

11. Rash, E., Verona, R. & Crowley, J. Human factors and safety considerations of night vision systems flight using thermal imaging systems. in *Proceedings of SPIE: Helmet-Mounted Displays II* **1290,** 142–164 (1990).

12. Hershberger, M. & Guerin, D. *Binocular rivalry in helmet-mounted display applications Technical Report AMRL-75-48*. (1975).

13. Browne, M., Moffitt, K. & Winterbottom, M. Improving the utility of a binocular HMD in a faceted flight simulator. in *Proceedings of the Interservice/Industry Training, Simulation, and Education Conference* (2009).

14. Browne, M. P., Winterbottom, M. & Patterson, R. E. Performance and comfort of monocular head-mounted displays in flight simulators. in *Head- and Helmet-Mounted Displays XV: Design and Applications, Proceedings of SPIE Volume 7688* (ed. Peter L. Marasco, P. R. H.) **7688,** (2010).

15. Ooi, T. L. & He, Z. Binocular rivalry and visual awareness: the role of attention. *Perception* **28,** 551–574 (1999).

16. Patterson, R., Winterbottom, M., Pierce, B. & Fox, R. Binocular rivalry and head-worn displays. *Hum. Factors* **49,** 1083–1096 (2007).

17. Abadi, R. Induction masking – A study of some inhibitory interactions during dichoptic viewing. *Vision Res.* **16,** 269–275 (1976).

18. Levelt, W. J. On Binocular Rivalry. 110 (1965).

19. Yang, Y., Rose, D. & Blake, R. On the variety of percepts associated with dichoptic viewing of dissimilar monocular stimuli. *Perception* **21,** 47–62 (1992).

20. Hollins, M. & Leung, E. in *Visual psychophysics and physiology* (eds. Armington, J., Krausfopf, J. & Wotten, B.) 181–190 (Academic Press, 1978).

21. Breese, B. On inhibition. *Psychol. Monogr.* **3,** 1–65 (1899).

22. Wade, N., de Weert, C. & Swanston, M. Binocular rivalry with moving patterns. *Percept. Psychophys.* **35,** 111–122 (1984).

23. Fox, R. & Check, R. Detection of motion during binocular rivalry suppression. *J. Exp. Psychol.* **78,** 388–395 (1968).

24. Blake, R. & Boothroyd, K. The precedence of binocular fusion over binocular rivalry. **37,** 114–124 (1985).

25. Liu, L., Tyler, C. & Schor, C. Failure of rivalry at low contrast: Evidence of a suprathreshold binocular summation process. *Vision Res.* **32,** 1471–1479 (1992).

26. Smith, E., Levi, D., Harwerth, R. & White, J. Color vision is altered during the suppression phase of binocular rivalry. *Science (80-.).* **218,** 802–804 (1982).

27. Julesz, B. & Miller, J. Independent spatial-frequency-tuned channels in binocular fusion and rivalry. *Perception* (1975).

28. Winterbottom, M., Patterson, R., Pierce, B. & Taylor, A. Visual suppression of monocularly presented symbology against a fused background in simulation and training environment. in *Proceedings of SPIE: Helmet- and Head-Mounted Displays XI: Technologies and Applications* 2.1–2.10 (2006).

29. Blake, R. & Fox, R. The psychophysical inquiry into binocular summation. *Percept. Psychophys.* **14,** 161–185 (1973).

30. Pelli, D. G., Palomares, M. & Majaj, N. J. Crowding is unlike ordinary masking: distinguishing feature integration from detection. *J. Vis.* **4,** 1136–1169 (2004).

31. Scharff, L. F., Hill, a L. & Ahumada, a J. Discriminability measures for predicting readability of text on textured backgrounds. *Opt. Express* **6,** 81–91 (2000).

32. Blake, R., Martens, W. & Di Gianfilippo, a. Reaction time as a measure of binocular interaction in human vision. *Investig. Ophthalmol. Vis. Sci.* **19,** 930–941 (1980).

33. Winterbottom, M. *et al.* Operational Based Vision Assessment Resarch: Depth Perception. *J. Australas. Soc. Aerosp. Med.* **9,** 33–41 (2014).

34. Winterbottom, M., Lloyd, C., Gaska, J., Wright, S. & Hadley, S. Operational Based Vision Assessment: Aerial Refueling Operator Visual Performance. in *Presentation at the Aerospace Medical Association Annual Meeting* (2015).

35. Parks, M. M. Th monofixation syndrome. *Trans. Am. Ophthalmol. Soc.* **67,** 609–657 (1969).

36. Hatt, S. R., Leske, D. a., Mohney, B. G., Brodsky, M. C. & Holmes, J. M. Classification and Misclassification of Sensory Monofixation in Intermittent Exotropia. *Am. J. Ophthalmol.* **150,** 16–22 (2010).

37. Hahn, E., Cadera, W. & Orton, R. Factors associated with binocular single vision in microtropia/monofixation syndrome. *Can. J. Ophthalmol.* **26,** 12–17 (1991).

38. Weakley, D. R. The association between nonstrabismic anisometropia, amblyopia, and subnormal binocularity. *Ophthalmology* **108,** 163–171 (2001).